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MAINTENANCE SIMULATION: RESEARCH AND APPLICATIONS

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Animated human figure models (HFMs) allow maintenance activity to be visualized on computer-aided design (CAD) geometry. These visual simulations have made it possible to simulate a much fuller range of human motion. Armstrong Laboratory's (AL) Design Evaluation for Personnel, Training, and Human Factors (DEPTH) project is taking advantage of these new technologies to improve weapon system design analysis, maintenance training, and logistics support analysis. DEPTH HFMs can be controlled with motion tracking devices (for hands and full body) or with models of maintenance tasks. Other DEPTH developments include Distributed Interactive Simulation (DIS) support, allowing DEPTH to communicate with other simulations and logistics document generation, for automated creation of technical manuals and support requirements.

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TABLE OF CONTENTS

PREFACE

Engineers must balance many requirements when developing a weapon system. Besides meeting the mission needs, they must consider weight, temperature, durability, reliability, and cost for each component. Unfortunately, one major contributor to life cycle cost is often overlooked -- maintainability. Until recently, a physical mock-up had to be built before maintenance problems were detected. Such mock-ups are usually built too late in the acquisition process to make cost effective changes. This problem is motivating the Air Force to create computer graphics simulations of human figure models (HFMs) so engineers can see (using real-time animation generation) and experience (using virtual reality hardware) maintenance on computer-based mock-ups. HFMs have been successfully used to simulate pilots; however, maintenance poses additional challenges for HFM control and functionality. This paper examines how the Air Force is using HFMs to improve the acquisition process. Beyond improved designs, simulations can also be used to demonstrate a task to trainees, and acquire logistics information used in technical manuals.

1. INTRODUCTION

When weapon systems were designed on paper, changes often forced the drafter to recreate entire drawings. Now, with computer-aided design (CAD), changes can be made relatively quickly and easily. Furthermore, analyses and simulations can be performed to balance mission and cost requirements optimally. Human factors engineering is particularly well suited for CAD analyses. Since humans interact with all machines, we are able to use simulation to ensure that people can use and maintain them as easily as possible. Considering human factors up front can pay off dramatically over the life of typical weapon systems.

This paper addresses how three-dimensional (3D) human figure models (HFMs) or agents can be used to simulate maintenance. HFMs discussed here differ from the arcade figures which can perform convincing looking activities. Although current arcade figures mimic a set of human motions realistically, they are not built to provide engineering analysis information. HFMs used for engineering and simulation, in contrast, emphasize data output over visual realism. They should be able to share a virtual space with CAD-generated objects and produce results useful for design evaluation, planning, training, or combinations of these.

In some of these simulations, a stationary HFM or mannequin is rendered in an environment with CAD geometry. To position the mannequin, the user either specifies the location and task, or the mannequin is simply placed in the drawing. These programs can give useful information about posture-based strength and can provide approximate tool movement envelopes; however, they do not simulate the complete task -- a critical limitation for some applications.

Some HFMs allow the user to drag end effectors (e.g., hands or feet) while joint limits, strength, and collisions are continually monitored. A standard mouse can be used, but input devices specifically designed for 3D input (such as body trackers) can make the simulations more interactive. In some cases,

body-tracking devices are either not convenient or not readily available; therefore, both standard input devices are usually supported in addition to 3D devices.

Armstrong Laboratory (AL) has developed methods to generate HFM movements automatically. The idea is to provide a "thinking" agent that acts like an experienced maintainer -- particularly helpful when the user lacks maintenance experience. Making these task networks flexible enough to handle obstacles is not trivial because it is extremely difficult to predict what alternate action will be best.

Some of the latest research with human models has involved distributed networks. The goal is to interconnect HFMs with other simulations to create comprehensive war-time scenarios. Since individual human activity is not only important in the cockpit, the activity of ground forces -- dismounted combatants and maintainers -- will be communicated over a network to weapon system simulations. This will allow virtual maintainers, controlled by an HFM simulation, to prepare virtual aircraft controlled by a flight simulator. These concurrent activities add detail and realism to simulations for training (maintenance and flight simulations) and analysis (theater level simulations).

2. UTILITY

The Air Force has typically used HFMs to simulate a specific job. For example, one of the earliest programs, COMBIMAN, is used to evaluate cockpit ergonomics. With the early success of this simulation, AL saw an opportunity to use HFMs to simulate maintenance; thus, the Crew Chief software package was developed. Crew Chief, which interfaces directly to several CAD systems, allows designers to determine vision, physical accessibility, and strength limitations of Air Force technicians (Ianni, 1991).

AL has developed a program called Design Evaluation for Personnel, Training, and Human Factors (DEPTH) to meet the needs of logisticians, human factors engineers, and designers. For maintenance simulation, DEPTH (Figure 1) integrates fully articulated HFMs that have the ability to animate tasks. Geometry from most CAD systems can be imported, modified, and exported. In addition to maintenance simulation, database and document generation software is integrated to produce the logistics information. DEPTH is discussed in more detail later in this paper.

Design

The historical life-cycle costs of weapon systems demonstrate that maintenance is a major driver -- thirty-five percent of the cost over the life of average Air Force weapon systems (Ianni, 1991).

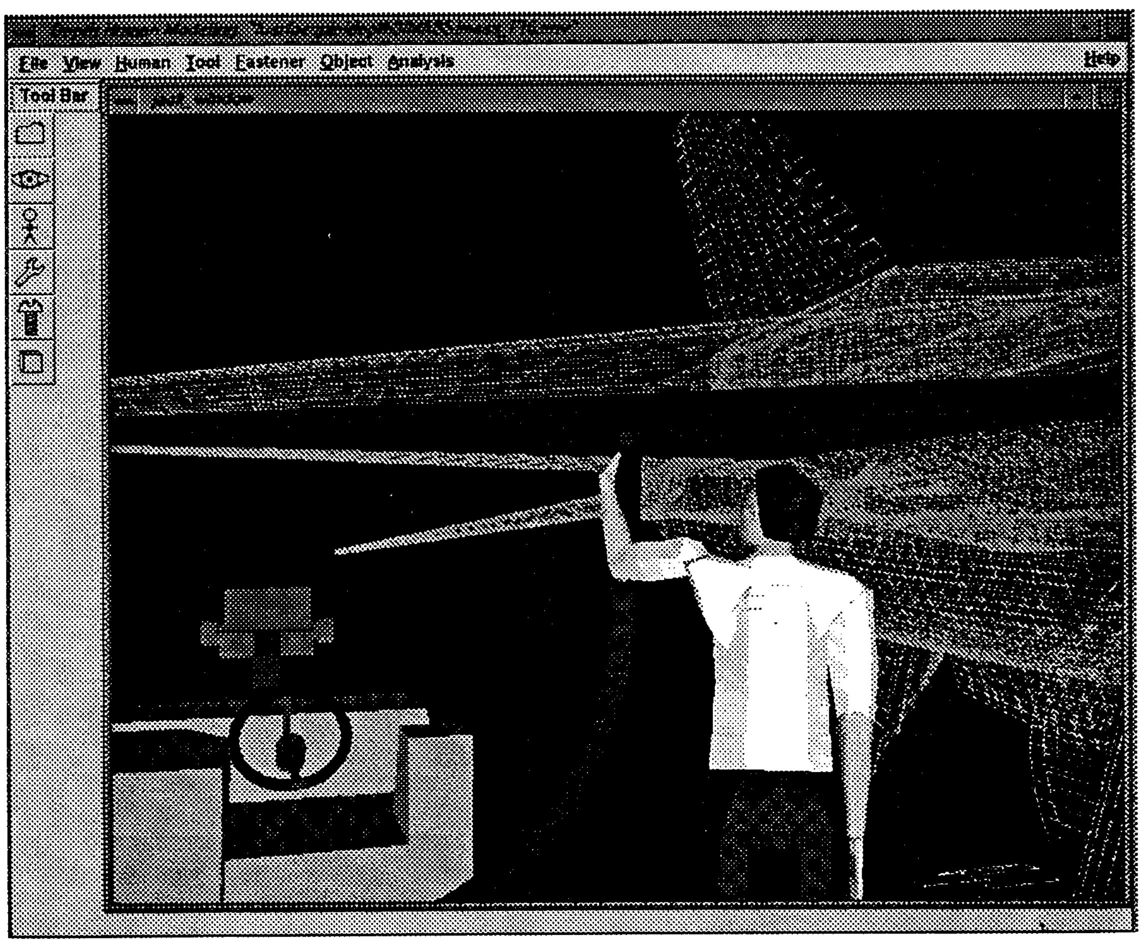

Figure 1: The DEPTH Virtual Technician

Therefore, the Air Force and its contractors are using HFMs to make diagnostics, replacement, repair, and upkeep as efficient as possible. HFMs provide the opportunity to discover, during design, ways to save time on the flightline. For example, when possible, line replaceable units (LRUs) with high failure rates should be easier to access than components with lower failure rates. Quicker maintenance translates into lower cost and more aircraft ready for the mission.

To determine the best configuration for weapon system components, 3D solid models are valuable, but without HFMs it is difficult to visualize human interaction. HFMs allow engineers to verify that maintenance is possible and see ways to make the designs even better. For example, a component may be barely out of reach; objects may obscure the visual field or impede movement (e.g., block the path of a tool); or an awkward posture may limit the ability to lift a component out of a rack. HFMs allow the simulation of many different scenarios while it is still relatively easy to make design changes. A mechanical or human factors engineer can use HFM software to discover the work envelope of a ratchet wrench, the visibility needed to remove a connector, and the strength needed to remove an LRU. These work envelopes can be treated as solid objects or maintenance access solids (MAS) so the space can be reserved throughout the design process.

Logistics Information

A technician needing to know how to perform a diagnostic or repair task can refer to repair guides known as technical manuals. The recent trend has been to use electronic technical manuals (ETMs) to reduce authoring costs and improve the presentation of the information. ETMs have made it possible for technicians to get nearly all the information they need -- including diagnostics and up-to-date schedules -- from a portable computer. Also, interactive ETMs (IETMs) have made it possible to eliminate extraneous information by automatically branching to the next step according to user responses. The user does not have to search for branches nor refer to addendum pages (Link *et al.*, 1987).

It is envisioned that the "scripts" used to automate HFM movement will be used to create IETMs involving physical maintenance activities. Figure 2 shows AL's approach to the problem. The CAD drawing is imported into the HFM's environment, where a process simulator is used to create an animation script of the task. The HFM runs through the task as the script is generated and possibly even discovers additional steps (e.g., additional removals to reach a fastener) that must be performed. After the command script is generated, it can be converted to natural language for use in IETMs. The conditional branching that occurs in the process simulator can also be converted into IETM tags to provide a logical flow to the task.

The Content Data Model (CDM), a specification used for IETM data storage, specifies how video

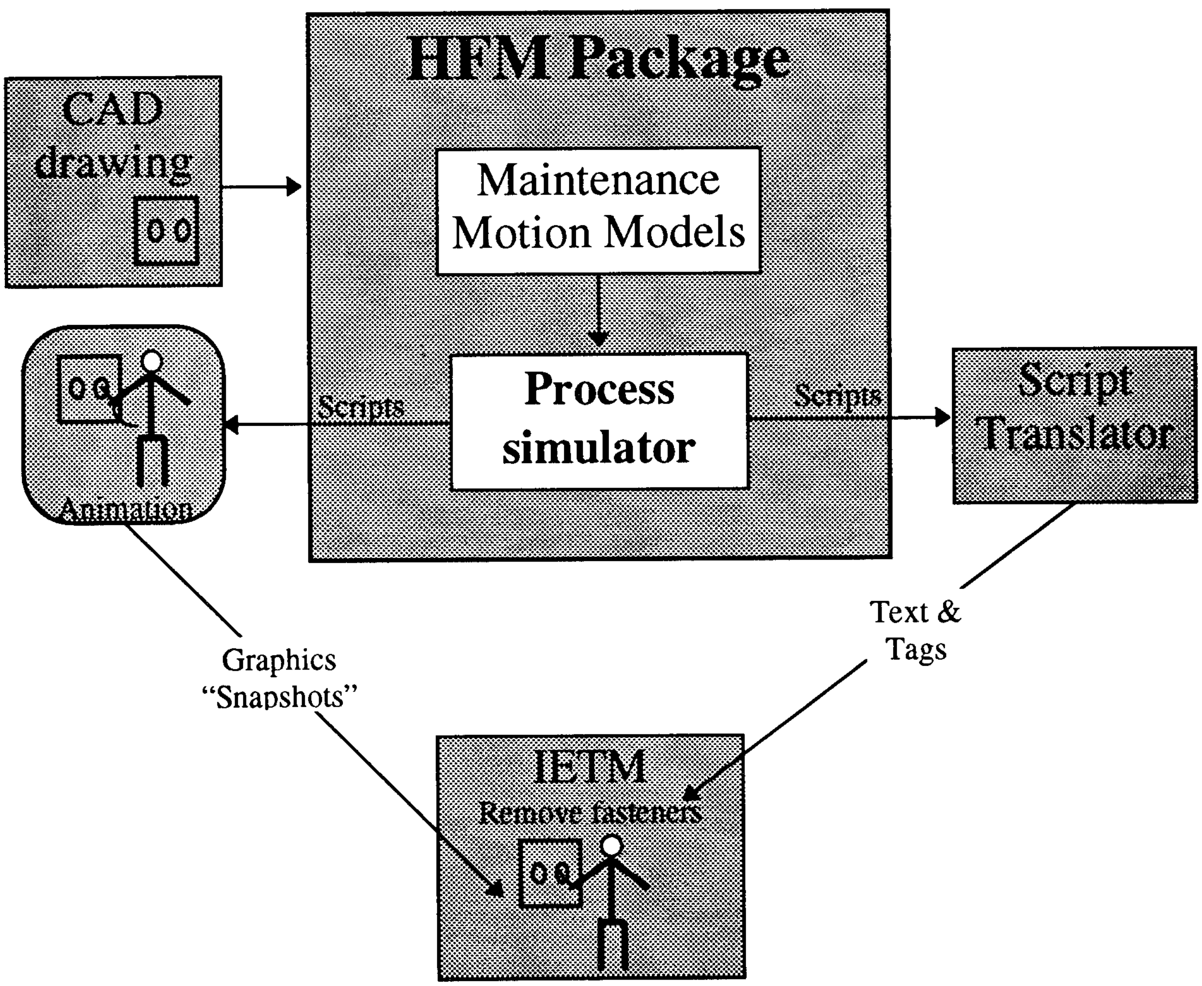

Figure 2: Technical Document Generation

can be integrated to make the procedures clearer. While text can be more efficient for an experienced maintainer, video can be valuable for new or infrequent tasks (Reser and DeDoncker, 1993; Earl and Gunning, 1990). However, video is costly to produce and store on disk. Additionally, it is not likely to be available for unique tasks, and these tasks can be the best candidates for visualization. In such cases, a spontaneous human figure animation can be useful. By specifying what they need to see, technicians can watch an HFM perform the task and discover the difficulties they may encounter when performing the task themselves (Zimmerman and Green, 1993).

The usefulness of HFMs is particularly evident in the case of aircraft battle damage. For example, a bullet penetrates deep into an F-16 aircraft that must be repaired quickly to meet the mission. The crew cannot tell from the initial inspections how extensive the damage is or even how to begin repairs. The officer in charge decides that a simulation is needed to ensure the crew understands the extent of the damage and how to fix it.

In the simulation, the path of the bullet -- shown using the F-16 computer graphics model -- indicates a critical controller card may have been hit. That card normally has a low failure rate and is seldom encountered during maintenance. No one on this crew has seen anyone remove this component before, but the simulation shows them what needs to be done. After watching the HFMs run through the procedures, the maintainers find that several components must be removed before they can reach the card. Furthermore, they discover that they may encounter some hazards. First, sharp metal fragments near the bullet's path may cause cuts on the hands, arms, and head. Even more hazardous is a potential chemical leak from a punctured pipe. After watching the simulation, the technicians are better prepared to repair this particular battle damage.

3. ENABLING TECHNOLOGIES

Model Control

Manipulating the HFM can be difficult with standard input devices. Selecting and moving objects in 3D space with standard input devices often requires combinations of keyboard and mouse actions. However, hardware devices exist to provide a more intuitive user interface. Some of these devices are listed below.

CAD Dials. Some workstations used for CAD come with a set of dials (typically six) for translation and rotation on X, Y, and Z planes. For HFM control, two dials each could be set up to move the upper arm, lower arm, and wrist. These dials are often used for view and object translation; however, they typically are not used to manipulate HFMs.

3D Track Ball. This "space ball" allows users to navigate through all three dimensions (i.e., planes) without any key or button combinations. The ball detects pressure applied by users on all three axes as they grip the baseball-sized grip. Force feedback provided by the track ball may allow the experience to be more intuitive. Although the 3D track ball is more intuitive than a mouse, some users require practice to become proficient.

The "Monkey." This unusual input device resembles a small monkey and has realistic joint limits. As users move the monkey's limbs, the joint angles are converted to digital signals. Some consider this device useful for positioning HFM limbs, but critics say it is impractical for most engineering purposes. This impracticality may be why few HFM packages used for simulation have Monkey interfaces.

Body Tracking. A more natural method to interact with 3D environments is provided with body tracking devices used in virtual reality systems. With a set of sensors mounted near certain end effectors and joints, the user's movements directly control the HFM. For example, detailed hand

movements are executed by means of a motion detection glove which is interfaced to the workstation (Burdea and Coiffet, 1994). However, body tracking may soon be possible without any sensors. Recently developed algorithms that analyze video images will soon make it possible to detect joint locations, segment lengths, and motion, thus eliminating the need for awkward body-mounted sensors for some applications.

The four types of input devices described above may not be accessible to all users. Consequently, developers are looking for software solutions to control the models. Recent research has been aimed at automating the movements of HFMs using motion models. Motion models are a sequence of HFM articulation instructions that make up a human activity. To be effective, the motion model must accept commands beyond simple movements such as *bend elbow*; the motion models must be able to construct complete tasks from commands such as *remove component.*

In addition to combining simple movements for increased abstraction, the models should be able to handle variations warranted by the situation. Conditional branching built into the motion model allows HFMs to make these situational adaptions. Thus, when an obstacle is encountered, the simulation does not simply give up; it looks for alternate ways to complete the task. For example, a defective LRU may be obscured by a large bundle of cables. The simulation might then determine that the cables must be removed before the sequence can be resumed (Badler *et al.*, 1993).

Distributed Processing

Real-time applications, such as HFM simulations, place high demands on computer processors. For example, animation of an HFM requires the calculation of proximity, shadowing, and interference as well as HFM-specific calculations like joint and strength limitations. Therefore, it is better to perform the calculations on separate processors.

Jack, the articulated figure modeling package from the University of Pennsylvania, has recently been ported to Silicon Graphics' (SGI) Performer to take advantage of its transparent use of multiple

processors. Performer, which provides a 3D graphics environment, improves response times by reducing geometry detail based on proximity and by using multiple processors to divide the real-time computational demands. Without the facilities provided by Performer or similar programming environments, it would be difficult to develop a real-time HFM simulation.

Distributed Simulation

Distributed simulation allows virtual environments to be shared over a wide-area network. A set of standards for intercommunication, called Distributed Interactive Simulation (DIS), has emerged for military simulations. Although continuous updates are not transferred between nodes (each node maintains its own copy of the "world"), it is possible convey position and basic actions of remote entities (DIS Steering Committee, 1994). Currently, this technology adequately describes the actions of aircraft and vehicles but only supplies rudimentary control of human movement.

Packets used for DIS communication are called Protocol Data Units (PDUs). PDUs are organized into several categories depending on the type of data being transmitted. The Entity State PDU allows some basic information to be conveyed about HFMs, such as the entity is a life form and it is performing a generic task. The tasks include postures (standing, kneeling, prone) and activities (walking, jumping, swimming), but there is no means to convey hand position or exact posture. Other than updates of the agent's position, there is no way to communicate detailed changes in state (Reece, 1994; Granieri *et al.*, 1995). The shortcomings for human movement control in DIS stem from the initial intentions for the protocol. The Entity State PDU was designed to describe tank warfare; thus, several fields of this packet are less than ideal for HFM simulation. Tanks, trucks, and aircraft can be realistically simulated with very few messages compared to HFMs.

The current DIS standard has no field to describe limb position; if it did, prohibitively large amounts of message traffic would be produced. However, without this detail, each interested node is forced to make a rough estimate of the posture (Reece, 1994). This lack of detail also limits the ability to

convey accurate maintenance simulations, but still allows information about task times to be factored into battle simulations.

Hundreds of sites participate in DIS exercises; therefore, message traffic per node must be kept to a minimum. Thus, descriptions of human motion transmitted over these networks include only the most critical task data. To make the motion continuous, a method called *dead reckoning* is used. This method requires each node to calculate the approximate position of entities relevant to their local simulation. Once the difference between the actual and projected position reaches a threshold, new position data is transmitted. The updates may cause the entities to suddenly change position, but it is hoped that these "jumps" will not impact the simulation if the threshold is set appropriately.

4. DEPTH

In the late 1980's, the Air Force saw an opportunity to analyze designs and generate logistics information by integrating task composition, database, and HFM software. Consequently, the DEPTH program was started to combine these technologies into one easy-to-use package. Figure 1 shows a DEPTH human model performing a typical flightline task. The specifics of the DEPTH architecture (presented in Figure 4) are below.

Architecture

DEPTH consists of an HFM package for design analysis, a task analysis assistant (TAA) for human factors analysis, and a tool for logistics information generation. The simulation capabilities in DEPTH are provided with the *Jack* software. The DEPTH shell gives *Jack* a user interface specifically for maintenance simulations. Highlights of *Jack* include (Armstrong Laboratory, 1994; Phillips, 1992):

- a detailed hand model,
- an articulated spine,
- motion path planning with obstacle avoidance,

- visual field tracking, and
- interfaces to body tracking devices.

Jack makes it possible to create variably sized HFMs capable of realistic movement. A spreadsheet is integrated to specify the size of body segments, joint limits, and position-based joint strength. It is possible, therefore, to have HFMs representative of Air Force technicians with respect to size and strength. Strength data can also be provided using the algorithms specifically collected for maintenance tasks for AL's Crew Chief program.

Maintainers perform complex tasks with their hands; therefore, the HFM must have grasping algorithms and detailed hand geometry. For example, the grasp on certain hand tools differs from the

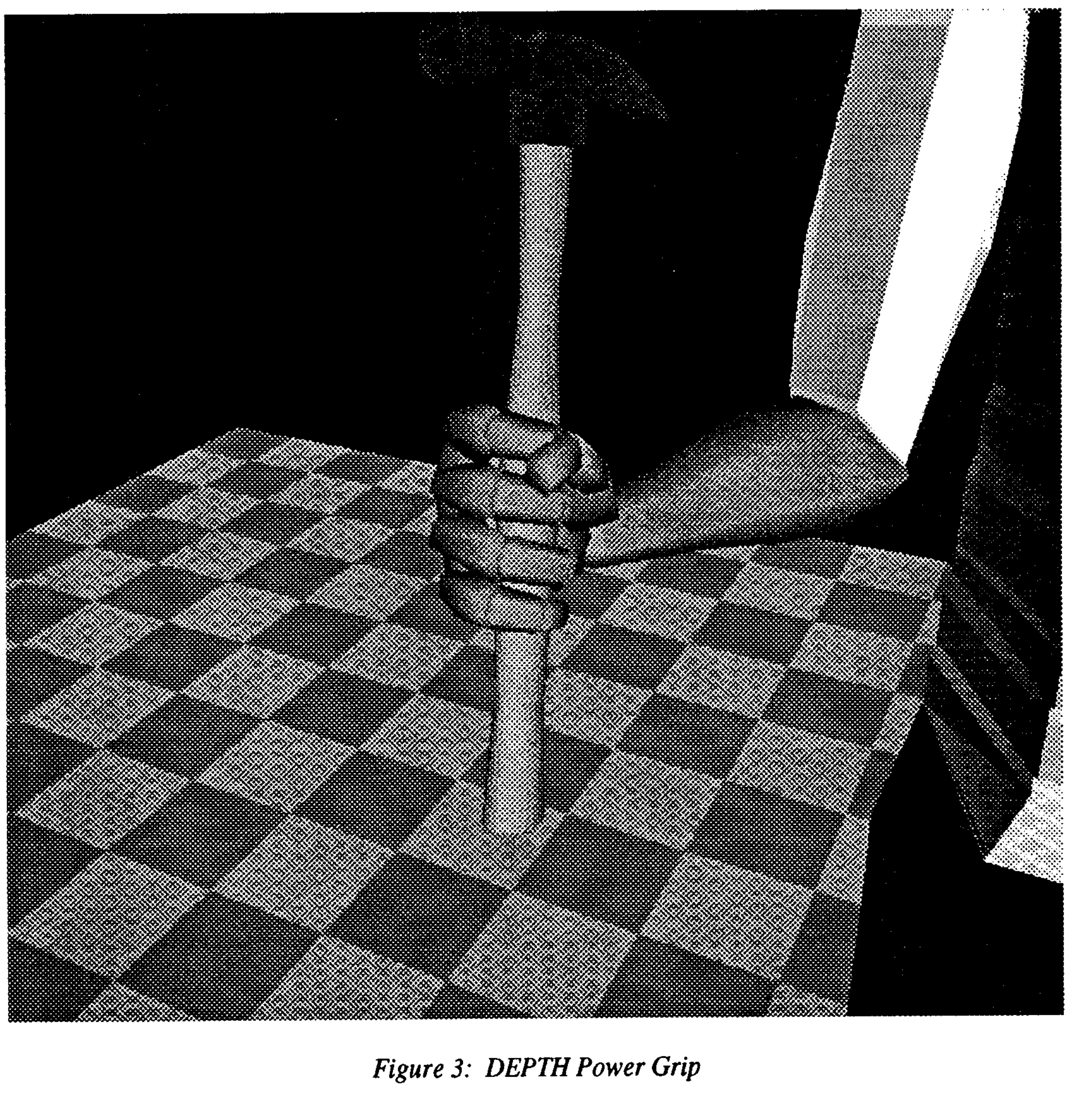

Figure 3: DEPTH Power Grip

grasp on small connectors. Hand tools require a power grasp (where the palm is used) while a fingertip grip is used for connectors. Figure 3 shows the DEPTH power grip used to hold a hammer.

In addition to graphical human factors analysis, DEPTH will be used to automate some of the acquisition process. Logistics Support Analysis (LSA) is one process that has been targeted. LSA ensures that the supportability needs of weapon systems are systematically created, tracked, and used throughout the life of a weapon system (U.S. Army, 1991). It is believed that the networks used to drive the DEPTH animations can also be used to generate the step-by-step instructions needed for LSA. Furthermore, DEPTH provides an excellent method to graphically depict the maintenance activities with action "snapshots" and animated segments (Boyle, 1991).

Figure 4 depicts the major software packages under the DEPTH umbrella. Currently, the task networking program is handled outside *Jack* by the Human Operator Simulator (HOS) developed by

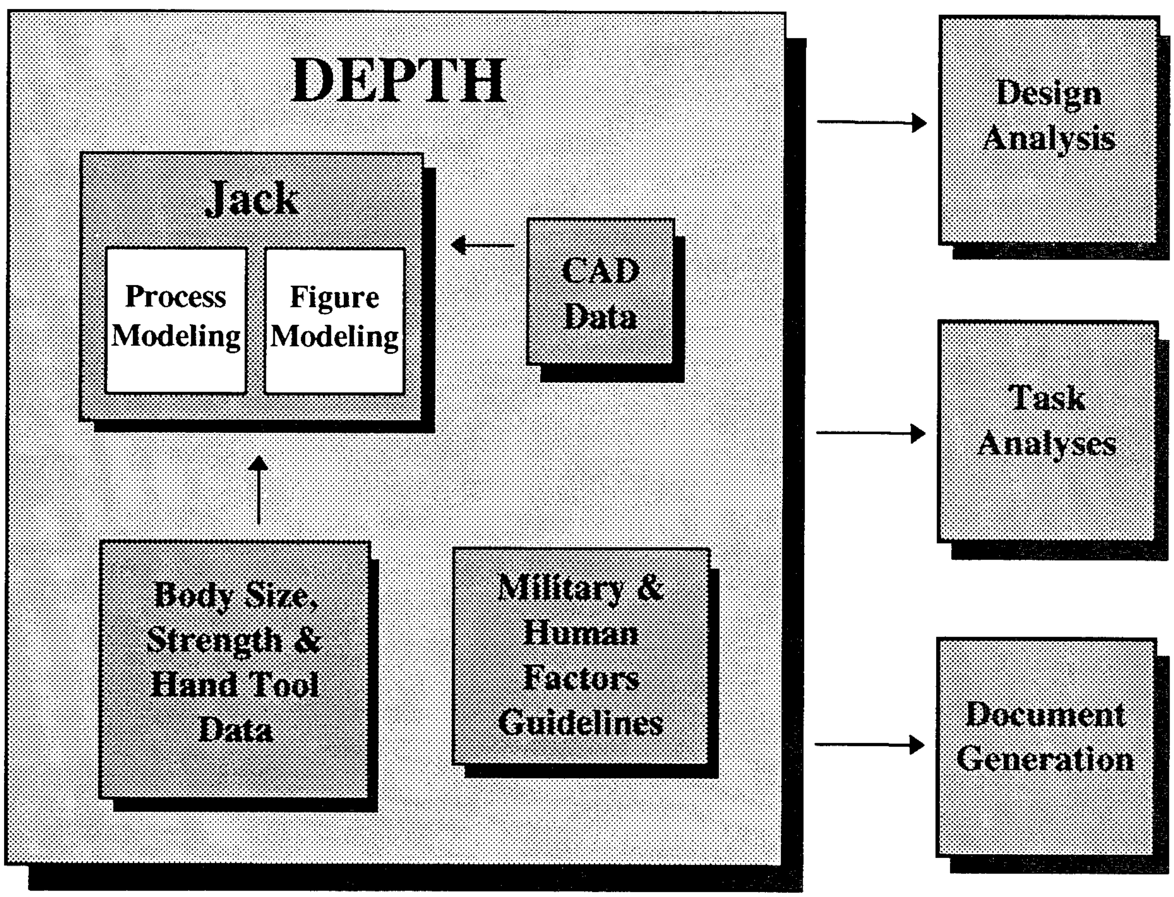

Figure 4: DEPTH Architecture

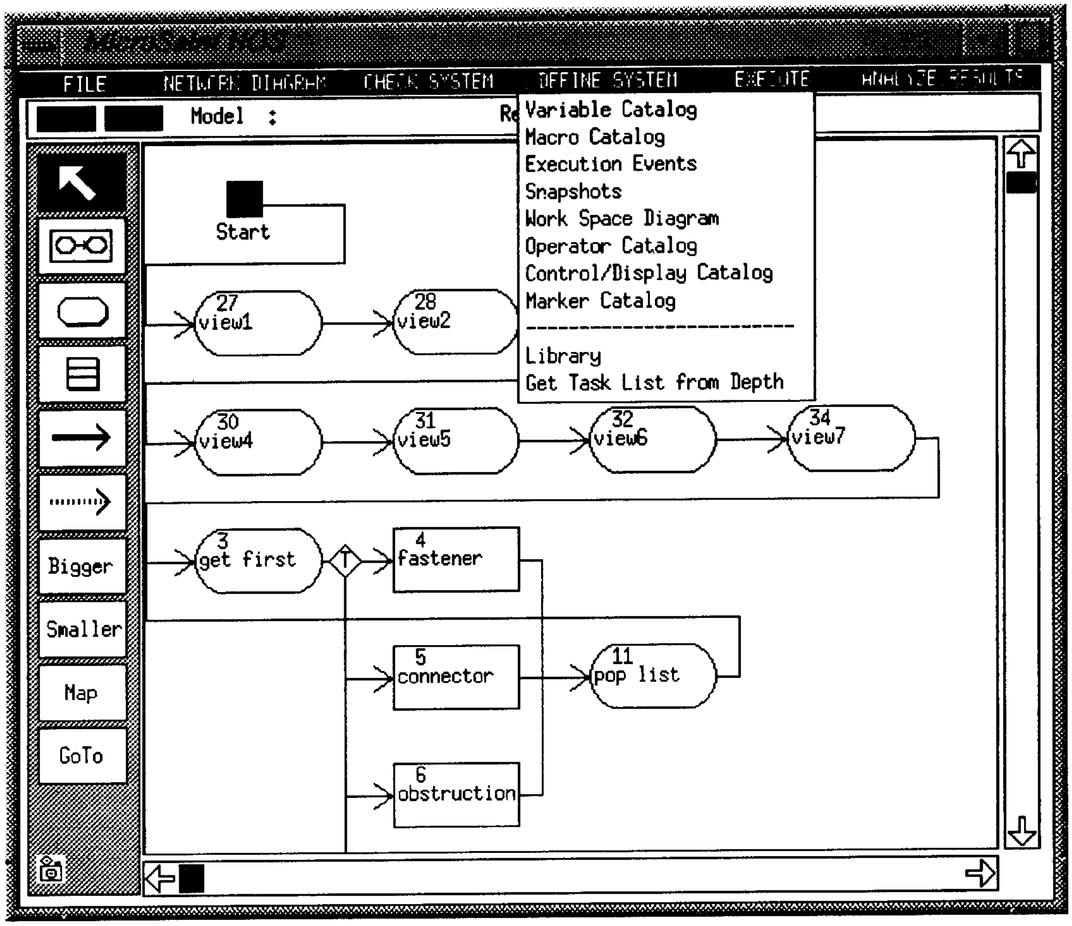

Figure 5: HOS Window

Micro Analysis and Design, Inc. Figure 5 shows the HOS window as it appeared in DEPTH Version 2.0. By early 1996, another task networking program called Parallel Transition Networks (PaT-Nets) will be the heart of animation scripting and, eventually, technical manual generation. PaT-Nets, which will soon have a graphical user interface, is embedded in *Jack* and has direct access to the dynamic environment. This direct access is expected to improve performance and decrease stalemates due to unexpected obstacles (Badler *et al.*, 1991).

Distributed Interactive Simulation

AL and the Defense Modeling and Simulation Office (DMSO) are investigating ways to use DIS to simulate humans. Software resulting from this work, called the Individual Combatant Simulation

System (ICSS), will provide DIS-controlled HFMs for the Air Force, Army, Navy, and Marine Corps. The primary focus of this program is combatant simulations but the Air Force is sharing the technology to develop maintenance simulations. The HFMs in ICSS will have physical, psychomotor, perceptual, and perhaps cognitive behavior elements. The maintainers will use much of the DEPTH technology to provide automatic control.

This technology is expected to provide many new opportunities. For example, it will allow a human factors analyst in Minneapolis to demonstrate a component removal problem to a designer in Fort Worth. This will be much more effective than standard telecommunications because they will share the same virtual environment and interact continuously. As changes are made to the design, both the analyst and the designer make recommendations until human factors and other requirements are met.

Human models will also be valuable for simulating wartime conditions for training and planning (Reece, 1994). Battle scenarios can be enacted while maintenance technicians rapidly prepare aircraft for the next sortie. This aircraft "pit-stop" is known as an integrated combat turn (ICT). Allowing technicians to run through ICTs under simulated conditions provides them with the "experience" to determine the best way to prepare for real battles. Logistics, supply, and mission planners should be able to make more informed strategies for specific battle situations using these simulations.

AL is planning to use distributed simulation to prove the utility of the Multifunction Aircraft Support System (MASS). MASS integrates the functionality of several flightline support systems into one mobile unit. Without simulation, it would be difficult to prove the utility of this unit. With distributed simulation, several live agents can use MASS simultaneously in many different situations. This will help to prove the MASS concept while refining the design.

Figure 6 demonstrates how distributed simulation will be used to simulate flight line activity. Three nodes, Flight Simulator 1 (FS1), Flight Simulator 2 (FS2), and DEPTH, comprise this distributed simulation. Communication between the three nodes can be facilitated by a local area network (LAN), or a wide area network (WAN) such as the Defense Simulation Internet (DSI) used for DIS communication.

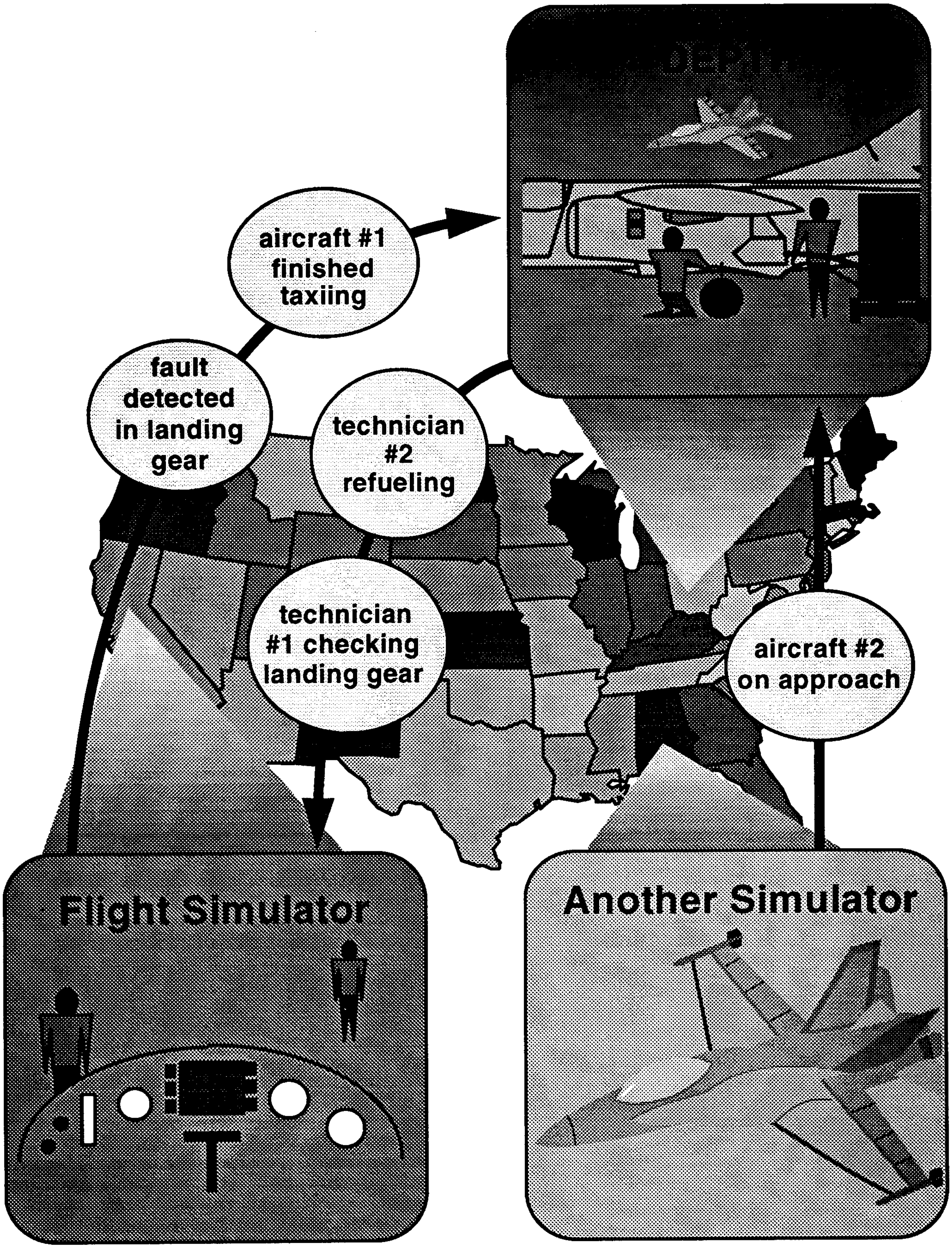

Figure 6: Distributed Simulation

The first message is sent by FS1: "aircraft #1 finished taxiing," informs the DEPTH node that the ICT may start. Before the ICT starts, a second message informs DEPTH that a fault was detected in the landing gear. Technician #1 is assigned to check out the fault in the landing gear, and DEPTH sends a message, received by FS1, that the landing gear is being checked. While Technician #1 is simulating fault isolation, Technician #2 simulates a refueling activity, and once again, DEPTH sends a message over the network. When FS1 receives the messages about the technician activity, it invokes its own simulation of technicians working on aircraft #1. The technician simulation on FS1 is not as detailed as DEPTH since the pilot does not need to know the details of maintenance.

As the technicians finish the ICT on aircraft #1, a message is received from FS2 that aircraft #2 is preparing to land. The DEPTH node then displays aircraft #2 in the appropriate location. This visual cue allows the technicians to prepare for the next ICT.

5. CONCLUSIONS

Human figure modeling offers many new possibilities for improving the Air Force maintenance process. It allows weapon system developers to visualize man-machine interfaces before any physical mock-up is built, thus making it possible to "tweak" designs and minimize maintenance costs.

Logistics data generation is a natural outgrowth of these maintenance simulations. Detailed task networks, generated to guide the HFMs through tasks, should also provide supportability information in the form of text, schematics, pictures, and animations. Consequently, LSA records and technical manuals can be acquired at a lower cost.

In a DIS session, these models can demonstrate how diagnostics, troubleshooting, and repair can impact air base operations. Realistic distributed simulations should be useful for training, scenario planning, and proving the utility of methods, tools, and support equipment in simulated air base operations.

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ACRONYMS

3D .... Three Dimensional

AL .... Armstrong Laboratory

CAD .... Computer-Aided Design

CDM .... Content Data Model

COMBIMAN .... Computerized Biomechanical Man-model

DEPTH .... Design Evaluation for Personnel, Training, and Human Factors

DIS .... Distributed Interactive Simulation

DMSO .... Defense Modeling and Simulation Office

DSI .... Defense Simulation Internet

ETM .... Electronic Technical Manual

FS1 .... Flight Simulator 1

FS2 .... Flight Simulator 2

HFM .... Human Figure Model

HOS .... Human Operator Simulator

ICSS .... Individual Combatant Simulation System

ICT .... Integrated Combat Turn

IETM .... Interactive Electronic Technical Manual

LAN .... Local Area Network

LRU .... Line Replaceable Unit

LSA .... Logistics Support Analysis

MAS .... Maintenance Access Solid

MASS .... Multifunction Aircraft Support System

PaT-Nets .... Parallel Transition Networks

PDU .... Protocol Data Unit

SGI .... Silicon Graphics, Inc.

TAA .... Task Analysis Assistant

WAN .... Wide Area Network

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